

Physiological Considerations Relevant To The Problem of Prolonged Weightlessness:

A REVIEW.*

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INTRODUCTION

Man's exploration of space may proceed either by gradual progression to longer flights at greater altitudes by man himself, or by larger increments of exploration using animal subjects. Both modes of exploration have their adherents. The former case is exemplified by the X-15 and Mercury Programs. In this case gradual extension of the period of weightlessness will be achieved one step at a time and the significant factors of weightlessness, equipment reliability, and safety will be explored simultaneously. The large-increment approach is exemplified by the Laika experiment. Here, advanced information may be obtained, and this may contribute notably to current manned space vehicle programs and provide data for extrapolation to future vehicles. Because the design criteria of future manned space vehicles depend strongly upon adequate experimental biological data, some of which, most notable that concerning weightlessness, can only be obtained in space, the early acquisition of such data appears mandatory for realistic planning of manned orbital and lunar missions.

The early history of the weightlessness problem, as studied principally by means of Keplerian flights in aircraft at the School of Aviation Medicine, Randolph Air Force Base, has been reviewed by Campbell and Gerathewohl (18). An historical review of studies performed at Holloman Air Force Base is also available (77). The significant work of Brown at Wright Air Development Division (WADD) on human performance capabilities during such flights is well known (14). Such experiments, although markedly limited in the duration of exposure to weightlessness (14 to 45 seconds), have served to disperse the many early uncertainties and fears which surrounded this problem. Whether data gathered during such flights, as well as the data available from short ballistic flights with animals (16, 60), are applicable to the problem of long-term weightlessness is debatable. In this review speculation will be made on some of the possible consequences of long-term weightlessness and methods derived for the prevention of untoward effects. The production of artificial gravity by rotation raises additional problems related to stimulation of the semicircular canals. The present conclusion is that, for a lunar mission of approximately 14 days, the weightless environment will be a requirement and the evidence at hand suggests that man will be able to function adequately if appropriate precautions are taken.

It is generally assumed that on a space platform, orbiting about the earth without drag from an outside atmosphere, the gravity-free state is realized in the

most perfect manner. While this proposition is entirely valid for the time scale and motions involved in physiological processes, it is not rigorously correct from a theoretical standpoint. Schaefer (124) has emphasized that the true weightless state in an orbiting vehicle of finite dimensions prevails only at its center of gravity. At any other point, the balance of centrifugal force and gravitational attraction is not complete. Minute as this difference is, the consequences may be considerable in terms of crew performance, particularly when free motions of objects on a time scale of several minutes or more are involved.

GENERAL METABOLIC EFFECTS

There appears to be a reasonably clearcut relation between metabolism and gravity (124). The metabolic costs of passive standing were first demonstrated by Benedict and Murchhauser in 1915 (10), and the data are shown in Table 1. Tepper and Hellebrandt (144), in a study of 75 young women, found a metabolic increment between recumbency and passively-assumed standing on a tilt table of +5.71 cal/sq m/hr or 16.25 percent. In 31 experiments on 12 healthy young women, Turner, Newton and Haynes (151) found an increment of +5.8 percent at 62 degrees tilt and 19 percent at 90 degrees. The increase in metabolism on passive standing arises presumably because of gravitational stimulation of proprioceptors in the muscles and joints of the lower extremities and, therefore, an increase in muscle tone.

TABLE 1
Metabolic Effects Of Posture (10)

Condition	O ₂ Consumed cc/minute	Energy output Calories/minute	Energy output Calories/hour	%
Lying Down	226-242	1.14	68.4	100
Sitting	234-260	1.19	71.4	104.4
Standing at ease	238-239	1.25	75.00	109.6
Moving Arms	516	2.53	151.8	222.0

The relation between metabolic rate and postural muscle activity suggests that the metabolism of weightlessness may be closely related to that of recumbency and inactivity. In spacecraft free motion may be limited, thus reducing exercise. Energy costs for self-propulsion under weightlessness may,

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on the other hand, be high until coordinated body movements are achieved by practice. In general, if space suits and restraint systems are used and crew tasks include largely monitoring and observation, there may be a need for programmed exercise. For instance, oxygen consumption of personnel in current space suits carrying out ordinary pilot activity over a 12-hour period averaged in one study 300ccs/min (161), and in another 390-480 ccs/min (145), the higher level (480) occurring during pressure suit inflation. No significant differences in oxygen consumption occurred when pilots performed first in summer flying suits and then in uninflated pressure suits. Inflation results in significant increases in metabolism due to the extra work necessary to move the distended joints.

Confinement and inactivity will probably be a characteristic of space flight but it is not possible presently to separate analytically metabolic effects related to inactivity from those which might be due to weightlessness *per se*. Experimental data collected during SAM Space Cabin Simulator confinements indicate very low metabolic rates (162) and it is instructive to extend the consideration of life in confinement as a partial analogue of life in a spacecraft. Studies of inactivity and confinement have been conducted along two lines: (1) the effects of immobilization and bed rest, and (2) the effects of submersion in water. The most detailed observations have been made under conditions of partial immobilization in a plaster cast.

IMMOBILIZATION AND BED REST

Partially as the result of the stimulus of World War II, but largely for purely medical reasons, the use of bed rest in the therapy of a wide variety of conditions came under intensive scrutiny (5, 19, 30, 36, 85, 95, 97, 115, 138, 140). Bed rest has been evaluated under a wide range of conditions including forcible restriction of normal individuals, comatose patients, spinal cord damage and paralysis and those seriously debilitated with extensive catabolic diseases. Complications of bed rest have been given as phlebothrombosis and pulmonary embolism, hypostatic pneumonia, decubitus ulcers, nephrolithiasis, constipation, myasthenia, orthostatic hypotension, pathological fractures and general catabolism. These undesirable effects of bed rest have raised fundamental problems concerning convalescence and rehabilitation of the medically ill, have resulted in the present practice of early post-operative ambulation and have stimulated a wide variety of studies of the relationship of gravity, inactivity and immobilization to normal function. These studies led Dock (35) to take exception to the anthropologist's view of the harmful musculoskeletal effects of gravity and to reassert the importance of activity to normal function.

In medically or surgically ill individuals it is not always clear which effects are related to the illness and which to recumbency alone. For the space flight problem of prolonged weightlessness emphasis should, therefore, be placed on studies of normal healthy individuals. In a now classical study by Deitrick, Whedon and Shorr (32) four healthy, normal

young men were immobilized in bi-valved casts extending from the umbilicus to the toes for six to seven weeks on a constant dietary intake. Under these circumstances a decline of 6.9 percent in metabolic rate occurred. Nitrogen losses averaged 53.6 grams and were associated with a lowered creatine tolerance and a decrease in muscle mass and muscle strength of the immobilized limbs. Calcium losses ranged from 9.0 to 23.9 grams. The calcium content of the urine was doubled and this, together with the absence of an appreciable increase in urine volume, a slight rise in urinary pH, and the failure of urinary citric acid to rise parallel with the increased urinary calcium, favored the precipitation of calcium phosphate in the urinary tract, although this did not occur. A deterioration in the mechanisms essential for adequate circulation in the erect posture was apparent as a tendency to faint on tilt-table tests. Blood volume declined, exercise tolerance decreased and resting pulse rate increased. Complete recovery of metabolic and physiological functions occurred slowly, requiring as much as six weeks in some cases. In the case of the astronaut no such severe effects are expected, but the effects of confinement and restricted activity may be considered additive with those of weightlessness.

SUBMERSION

Water immersion has been suggested as a simulation of weightlessness. The simulation derives from the fact that the relative densities of the human body and water are nearly the same, which almost abolishes the "contact forces" and the resulting internal deformations. The body is still acted upon by "field forces" due to the relative densities of different parts of the body. The simulation is only partial and is complicated by the fact that the body is surrounded by water rather than air, and inertial forces are generated due to the resistance of the water when the subject moves. Although water immersion has been used widely to study spatial orientation, sensory deprivation and acceleration protection, all areas of interest and application for space flight, only recently have such studies been related to the problem of zero g. It is characteristic of the initial studies that for the most part no experimental controls were provided and mechanisms for the prevention of effects not examined.

In a study by Graveline and Balke (51) large nitrogen losses were observed but only relatively minor changes in calcium excretion. Polyuria was marked. Some increase in WBC values occurred and the hematocrit reached 57 on the third day of the seven-day study. Average caloric intake during submersion was 1900 Calories. A comparison of pre- and post-immersion work capacity, orthostatic tolerance and g-tolerance was made. All measurements paralleled those expected on the basis of bed-rest data but the changes were early and marked. Treadmill tests showed decreased work capacity; tilt-table tests showed a decreased orthostatic tolerance; and centrifuge tests demonstrated a decline in $+G_z$ tolerance. In the latter case, measurements of $+G_x$ tolerance would have been more desirable if the data are to be applied to space flight.

Graybiel and Clark (54, 55) have also used submersion to assess the effects of prolonged weightlessness. In their experiments, subjects were exposed only 10 hours per day for two weeks, the remainder of the time being at bed rest except for experimental periods. Systematic attempts were made to eliminate a number of effects due to sensory deprivation; i.e., someone was with the subject 24 hours a day. Although no decrements in muscular strength and coordination occurred, marked postural hypotension developed during and following the period of immersion. In the Navy experiments at Johnsville (9, 12) 18 hours of immersion of experienced divers produced decrements in positive acceleration tolerance that were within the normal range of daily variations. In a study involving immersion to the level of the neck the important role of hydrostatic forces in producing "negative-pressure breathing" was described which may account for many of the physiological findings in other studies.

Because of the reduction of metabolic needs occasioned by weightlessness, interest has been expressed in sleep requirements for the crew of a space vehicle. McKensie, Hartman and Graveline (106) have evaluated sleep during immersion and found a reduction in the total sleep requirement, a constriction in the range of sleep states and a progressive improvement in the stability of sleep states. These authors suggest that sleep schedules in space may be shorter than normal, that subjects easily can be aroused to meet emergencies and during the experimental periods observed no effects attributable to sleep loss. The observations of Lilly (100) tend to confirm these findings. Graybiel and Clark (54), on the other hand, found no sleep changes and attribute such effects to individual differences and motivation, reflecting subject selection. They point out that men on long submarine cruises typically sleep most of the hours when not on duty. Although psychomotor performance may decline during immersion studies, such changes also may be related to motivation (21, 71, 100). Further studies are needed in this area.

CARDIOVASCULAR EFFECTS

It is widely believed that the postural hypotension which develops during prolonged inactivity, whether produced by bed rest or by submersion, reflects a profound change in endovascular reflex responses (55). The experimental evidence appears, however, to support the view that these effects are complex and may be related to a redistribution of fluid and electrolytes within the body resulting from recumbency and inactivity, an alteration in the mechanical properties of blood vessels and a decrease in circulating blood volume as well as peripheral vascular reflex effects. Bed-rest data characteristically show a decline in blood volume. That of Taylor *et al* (141) is given in Table 2.

Stretch receptors are known to exist in various parts of the circulatory system (6). The characteristics of the redistribution of the blood volume accomplished by changes in posture, cuffing of the limbs and obstruction of the vena cava have suggested that volume receptors might exist in the upper half

TABLE 2
Blood-Volume Changes During Bed Rest (142)

	Plasma Vol. ml	Hematocrit percent	RBC Vol. ml	Blood Vol. ml
Control	3334	45.7	2806	6140
Post Bed Rest	2816	49.5	2751	5568
Difference	-518	3.8	-54	-572
Percent	-15.5			-9.3

of the body. Attention was drawn to the neck itself by experiments that suggested that the application of a cuff around the neck might modify salt excretion (154). However, this has not been confirmed by others (114).

Recently, considerable attention has been directed to volume receptors within the thorax. Gauer, Henry, Sieker and Wendt (47) demonstrated that negative-pressure breathing promoted an increase in urine flow in dogs while positive-pressure breathing promoted a decreased flow (38). These observations have been confirmed in man (79, 129) and it seems reasonably clear that the response is an excretion of water with no primary effect on the rate of excretion of sodium or other solutes. The response is blocked with vasopressin (13, 113) and no increase in urine flow occurs while the subject is under maximum water diuresis and the secretion of anti-diuretic hormone is, presumably, suppressed completely (13). The anti-diuretic response can be partially or completely inhibited with alcohol (113). Surtshin *et al* (137) have demonstrated that the diuresis of negative-pressure breathing is not significantly affected by renal denervation. Thus, the efferent arm of this reflex seems to be a diminished supply of anti-diuretic hormone rather than some peripheral neural component.

Henry and his co-workers (72, 73) demonstrated that distention of the dog left atrium with a balloon resulted in a pronounced diuresis and that the response to negative-pressure breathing was either abolished or reduced by section of, or application of cold to, the vagus nerves. They also recorded neural discharges from the vagus nerve and by relating peak activity to events of the cardiac cycle were led to conclude that the receptors primarily respond to stretch rather than to pressure.

Henry and others (74) seemed to have excluded distention of the pulmonary arterial and venous system, except, perhaps, for that portion of the pulmonary vein that lies within the pericardium. Love *et al* (102) demonstrated that the amplitude of the pulsations of some parts of the intrathoracic vascular system might be the important stimulus. They reported that pulsatile-pressure breathing around a mean of zero, or at a mean positive pressure of 20 mm Hg, promoted an increase in urine flow; whereas, nonpulsatile positive-pressure breathing did not.

In assessing the significance of this atrial reflex Henry, Gauer and Sieker (74) reported that changes in blood volume from -30 percent to +30 percent influenced pressure concordantly throughout the

circulatory system, and concluded that stretch receptors in the left atrium could, therefore, be influenced by changes in volume. Recent studies by Lewis *et al* (99) have demonstrated the extent of the blood shift to the lungs which takes place on recumbency.

Supradiaphragmatic inferior vena cava constriction, which results in an expansion of the low-pressure venous system below the constriction and a depletion of blood above, results in an increase in the secretion of aldosterone (8). The effect is reversed by a rapid infusion of blood above the constriction. The evidence suggests that a neuro-hormonal hemodynamic mechanism plays a role in controlling aldosterone secretion. Farrell (42) has suggested that stretch of the right atrial receptors evokes afferent impulses that lead to the inhibition of the release of another hormone from the diencephalon which, in turn, regulates the secretion of aldosterone by the zona glomerulosa of the adrenal gland. This reflex might result in some increased loss of sodium chloride from the body.

TABLE 3
Biochemical Analysis of Urine Samples
Obtained During Submersion (51)

	Urine Volume cc/24 hours	Na	K mEq/24 hours	Ca	Cl	PO ₄
Control	1170	251.7	81.1	10.8	74.9	49.2
Day 1	3200	549.5	83.1	11.8	137.1	35.1
Day 2	2900	345.0	79.4	7.8	77.6	45.1
Day 3	3000	221.6	103.6	12.9	55.1	61.7
Day 4	1750	175.7	80.6	7.5	39.2	51.1
Day 5	2100	131.1	70.6	8.7	43.6	42.3
Day 6	1800	192.3	74.3	10.4	50.1	45.4
Day 7	1550	307.5	40.7	10.9	66.7	39.3

It seems possible that the submersion data of Graveline and Balke (51) shown in Table 3 may be explained in the following manner: submersion (including the attendant inactivity) results in blood shifts within the vascular system, leading to diuresis and natruresis, perhaps due to the stimulation of stretch receptors in the thorax and alterations in aldosterone secretion. There results, over a period of time, a decrease in circulating blood volume, a cumulative electrolyte imbalance and a translocation of fluid to the extravascular spaces, the latter accounting for the clinical evidence of plethora reported. These complex changes, resulting in a diminished blood volume and changes in vascular reactivity, account for the orthostatic hypotension and a diminished g-tolerance. Further studies will be required to confirm such speculation and to define the mechanism of fluid, electrolyte and reflex alterations which appear to occur during recumbency, submersion and inactivity. In the experiments of Graveline and Balke subjects were submerged only to neck level. Beckman *et al* (9), in repeating these experiments, suggest that the physiological findings can be attributed to the negative-pressure breathing produced by this type of submersion. In any case, exposure to zero g may result in a redistribution of body fluids and attention should be given to the means of preventing any resulting orthostatic effects.

The mechanical properties of blood-vessel walls depend, to a degree, on the water and electrolyte content of their smooth muscle. In an extensive review, Tobian (146) has suggested that water and ion accumulation or depletion in vascular walls might result in passive alterations in the lumen of blood vessels and a change in resistance to flow, particularly in the region of the small vessels and arterioles. Alterations in ionic concentration may affect smooth-muscle kinetics and membrane potentials because there is ample evidence that vascular reactivity, both in vivo and in vitro, is affected by ionic concentration. In reflexogenic zones, such as the carotid sinus, locally applied drugs markedly affect reflex responses, thus revealing the importance of the coupling of the nerve endings to the vascular wall (75). Accordingly, it is supposed that alterations in the mechanical properties of blood-vessel walls, such as the carotid sinus, may affect vascular receptor mechanisms and a similar general mechanism may affect peripheral vascular responses (125).

In the peripheral vascular bed, parallel increases of arterial and venous pressure results in a passive distention of vascular bed and a decreased resistance to flow (98). No fundamental disturbance in such physical peripheral vascular relations is anticipated in the weightless state and the pressure gradients should be similar to those of recumbency. During tilt-table tests following submersion experiments (52), the records of blood pressure and heart rate do not suggest a diminished reflex attempt by the body to compensate for the hydrostatic forces but rather a failure of peripheral response mechanisms. Although the carotid sinus and other similar receptors are thought to be "slowly adapting", nobody has ever claimed that they cannot adapt at all. Adaptation is not a likely explanation for submersion effects, however. In hypertension such adaptation may occur over months or years. Thus Schmidt (125) has suggested that the baroreceptors in the hypertension may be the victims rather than the aggressors, and it remains to be seen whether the same corollary holds for weightlessness.

The relation between circulatory integrity and muscular and osseous atrophy of disuse is not clear. The literature has been reviewed by a number of authors (49, 70, 109) particularly with reference to the circulatory disturbances and alterations in bone growth following anterior poliomyelitis. McPherson and Kessel (109) were unable to attribute footblood-flow variations in poliomyelitis to differences in muscle bulk or tone, the efficiency of the venous pump mechanism, metabolism, or the temperature of the feet, legs or whole limbs. There was no correlation between muscle power and blood flow and the capacity of the vasculature to respond to usual vasomotor stimuli was not much affected by prolonged disuse. Arterial narrowing is generally recognized in prolonged paralysis and hypoplasia of the arteries in the paralyzed limb suggested (49). Growth of the paralyzed limb is enhanced by sympathectomy in humans (70) and rabbits (49). The effect is, in part, due to the maintenance of normal or near-normal blood flow to the epiphyseal line in growing children or animals.

A frequency concomitant of bed rest is the occurrence of phlebothrombosis and pulmonary embolism. Hunter (80), in his extensive study, found an incidence of deaths due to pulmonary embolism in bed-rest patients of approximately three percent. Although only 34.7 percent of patients exhibited muscle atrophy, approximately 64 percent of this group had thrombosis. The incidence of embolism peaks around the fifth or sixth day of bed rest and then again in the third week. It is thought that thrombosis has its genesis in the reduced venous pressure in the legs and pelvis at bed rest with partial collapse of these veins (96). Muscular exertion in the bed-rest patient may then result in the release of an embolus. Abnormal local pressures on the leg such as a popliteal pillow or the use of a bed break at the knees are thought to contribute to thrombus formation. Planned and supervised exercise, turning, relief of abdominal distention and deep breathing are recommended as preventive measures.

It has been proposed that exposure to prolonged weightlessness might result in the deterioration of the cardiac musculature and, ultimately, heart failure (136). Although a decrease in cardiac rate may occur during zero g associated with a more general decrease in body metabolism, the major physical elements of stroke work should be unaltered. The principal contributions to stroke work occur in overcoming the inertia of the blood, the production of flow against viscous forces and the distention of the vascular system, none of which will be altered by zero g. The absence of gravity should not alter the hydrostatic load on the heart. Experiments during acceleration on centrifuges have demonstrated an hydrostatic balance point at the level of the heart in the arterial system (94). Bed-rest studies, such as those of Taylor *et al* (142), do show cardiac effects. In their experiments a 17-percent decrease in cardiac volume and an 8-percent decrease in transverse cardiac diameter were observed. Although the heart rate increased approximately 0.5 beats per minute per day of bed rest, no change in cardiac output occurred. The basal metabolic rate fell an average of 8.8 percent. Cardiovascular functions were the last to recover from the three- to four-week, bed-rest period, taking as long as seven weeks in some instances.

Passive exercise by means of an oscillating bed has been shown to modify the metabolic and physiological effects of immobilization (163). In general, metabolic abnormalities were reduced by approximately one half; and deterioration of cardiovascular postural mechanisms was largely prevented, although the experimental subjects continued to be confined to casts. When the oscillating bed was not used, elastic bandages applied to the legs prevented orthostatic hypotension on the tilt table (33).

Blood shifts to the chest, if they occur during zero g, can be reversed by positive-pressure breathing. This procedure may also be of value in preventing atelectasis which is thought to occur in cabin atmospheres of high oxygen content. Procedures and equipment for several sessions of positive-pressure breathing per day for each member of the crew should be considered.

BONE DEMINERALIZATION

Bone is a tissue in dynamic equilibrium in which the osteoblastic activity of mineral deposition is in balance with the osteoclastic activity of mineral absorption (2, 3, 152). Diminution in bony mass may result from either increased bone resorption or from decreased bone formation. The former disorder is characteristic of hyperparathyroidism (osteitis fibrosa generalisata). In the latter case, either failure to deposit calcium (osteomalacia) or underactivity of the osteoblasts in laying down bone matrix (osteoporosis) may be the basic defect. Stress and strain on the bony members is required for normal osteoblastic activity so that bone atrophy of disuse is a special form of osteoporosis. Osteoporosis is thus a disorder of tissue metabolism and only secondarily one of calcium metabolism.

Extensive studies of calcium metabolism are available in the literature (62, 66, 107, 116, 132, 134, 139). Of the total blood calcium of 10 mg/100 cc, approximately 3 mgs/100 cc is under the control of the parathyroid which monitors and regulates the blood-calcium level under ordinary circumstances. Radioactive tracer studies suggest that, at least in young animals, the body calcium is highly mobile and as much as 100 percent turnover per minute has been observed. The bulk of the body calcium is thus highly mobile, and it has been suggested that bone acts as an ion-exchange column with calcium transported to and from bone by passive physical chemical mechanisms (107). Others have emphasized the role of citric acid in solubilizing calcium in bone (calcium citrate) for transport to the blood stream. The role of citric acid is believed to be related to cell activity under the influence of the parathyroid and Vitamin D.

The relation of the compression forces of weight-bearing and muscular contraction to bone growth and integrity has long been recognized (157). In experimental animals, bone rarefaction is related to the relief of muscular compression forces (48). Methods of study have included tenotomy, immobilization in plaster, nerve paralysis, joint injury and simple fixation (4, 48, 69). Wyse (167) has studied paraplegics for evidence as to whether disuse atrophy is related to circulatory changes, the stress of muscular contraction or weight-bearing. He showed that weight-bearing, as induced by a tilt table, and circulatory changes, as induced by an oscillating bed, were not involved in disuse atrophy in paraplegics. In flaccid paralysis the stresses of muscular contraction on bone are absent. He concluded that muscular contraction is the stimulus to osteoblastic activity.

There is no evidence that bone nutrition and structure is dependent to any degree on its nerve supply *per se* (29). Secondary effects may occur when interruption of the innervation of the surrounding tissue alters normal function. Bone changes in myopathies are not induced by genetic effects, such as defects in mesodermal development, or by hormonal changes, but are effects of disuse (156).

Although growth of the extremities depends upon and can be altered by variations in the blood supply to the epiphyseal line (70) and the nature and course

of bone diseases depends upon the vascularization of the diseased area (78, 160), the evidence that disuse atrophy is related to alterations in blood supply is not convincing (48, 70, 167). Histological examinations of bones of animals during experimental disuse atrophy have demonstrated that both removal and formation of bone are associated with increased vascularization, generally related to the amount of bone present; but such vascularization is not regarded as the primary cause of the atrophy (48). Isometric contractions induced by faradic stimulation of immobilized muscles reduces the experimental rarefaction of bone despite the hyperemia which is induced (48).

Atrophic bone is apparently normal in chemical composition and basic mechanical properties (4). Atrophic bone grafts take in normal limbs and normal bone grafts take in the atrophic limb. Disuse has apparently no effect on graft-healing.

The extreme mobilization of calcium which occurs during recumbency, disuse or immobilization and the high incidence of urinary calculus in such conditions as spinal-cord injuries has excited interest in urinary calcium excretion in these conditions (20, 28, 31, 87). Factors affecting normal urinary calcium excretion such as age, intake, etc., have been reviewed by Knapp (88). Because the osteoporosis of disuse is a disorder of tissue metabolism and not primarily of calcium metabolism, serum calcium and phosphorous levels are generally normal (2, 108). Serum phosphatase, an index of osteoblastic activity, should not be elevated but, if anything, perhaps decreased.

The incidence of urinary calculi in paraplegia may be as high as 34 percent (45). This high incidence is related to the elevated urinary calcium level, a reduced urine volume, infection and changes in urinary pH. No relation has been demonstrated with age, level of injury, spasticity, flaccidity, intake of calcium, blood-calcium level or consumption of vitamin A or D. Low-calcium diets did not lower the hypercalcuria (165, 166). High-calcium diets may raise the urinary calcium but produce a positive calcium balance. In fractures urinary calcium excretion increases until the period of protein destruction is past before becoming constant (78). During maximum calcium excretion an increase in dietary calcium produces only a small increase in urinary calcium. If phosphorous is added to the diet as well as calcium, no change in urinary calcium excretion occurs. The relation between urinary citric acid and the solubilization of urinary calcium has important implications for urinary stone formation (128).

MUSCLE ATROPHY

The possibility of muscle atrophy occurring during weightlessness has been recognized (55, 127, 119). In the literature the problem of muscle atrophy has been extensively treated in connection with the so-called trophic influence of the nervous system on non-nervous tissue (27, 150). Bone comes under the trophic influence of the nervous system through the medium of the stresses and strains imparted by muscular contractions (149). It is also possible that muscular contraction influences bone blood flow,

where it acts as a pump mechanism affecting arterial supply and venous drainage.

In the case of muscle itself, it is important to recognize and distinguish the role of simple inactivation of the muscle from the consequences of nerve section (22). Nerve section produces pronounced muscle degeneration so that as much as 86 percent of the muscle weight may be lost in 12 weeks (23). The rate of atrophy following nerve section is related, at least in part, to the rate of growth of the species (76). Simple disuse or inactivation atrophy, in contrast, proceeds slowly. However, it is apparent that both the physical integrity of the innervation and activity are required for the maintenance of the normal trophic state (90, 149).

Reid (121) and Chor and Dockhart (22, 23) have contrasted the results of nerve section and those of simple disuse atrophy. Reid severed the spinal cord at L4 and S2, cut the dorsal roots bilaterally and the ventral roots on one side. Dorsal root section alone does not produce trophic changes in muscle (147). In the completely denervated side, reflexes were absent. An abnormal strength-duration curve was observed with a chronaxie of 0.64 uf. Atrophy was pronounced and fibrillation occurred. On histological examination, there was a marked increase in the number and size of subsarcolemma nuclei which were less deeply stained (148). On the "disused" side (motor root intact), the reflexes were absent but spontaneous movements were observed. No fibrillation occurred and the strength-duration curve was normal with a chronaxie of 0.08 uf. Muscle weight loss was 38.5 percent in ten weeks. The decreased muscle bulk resulted from a decreased sarcoplasm and additional packing of muscle fibers.

The atrophy resulting from tendon section is nearly as great as that due to nerve section but the cause is thought to be primarily disuse (101). The atrophy accompanying joint lesions may be severe but is usually selective, occurring largely in the extensors (69). The etiology is thought to be related to pain, reflex irritation or inflammatory products in addition to disuse. Langley (93) has proposed that, in nerve section, the atrophy arises from fatigue related to the fibrillation which is usually observed. This theory has gained little support and experiments in which quinidine was used to depress fibrillation, although not entirely successful, appear to indicate that the theory has little merit (131).

In a careful study by Fudema, Fizzell and Nelson (46) the electromyogram was used to follow the course of disuse atrophy. They utilized a bilateral external splinting technique in cats, thus avoiding the complications which frequently accompany the use of casts. The maximum of the integrated electromyographic reading from the anterior tibial muscles on both sides in response to percutaneous supra-maximal stimuli to the peroneal nerve was recorded every four days. A gradual decline characteristic of simple disuse atrophy was observed over 101 days. In addition, motor unit potentials decreased in amplitude, presumably related to a reduction in the mass of individual fibers.

STIMULATION AND EXERCISE

A number of investigators have attempted to maintain muscle weight following nerve section by passive movements and electrical stimulation. Passive movements result in little or no effect (41). Eccles, however, was able to maintain flexor weight to some degree by daily stimulation. Extensors generally were not affected. No form of artificial stimulation appeared to be capable of maintaining fully normal muscles. Two hours of stimulation daily appeared to be no more effective than a few seconds. Fisher (43) found that stimulation did not affect muscle power to the same extent as muscle weight, presumably because of the severe ultra-structure derangement associated with nerve section.

In the submersion study of Graybiel and Clark (54, 55), muscle strength was fully maintained and endurance, as measured on the treadmill, was reduced in only two subjects. These results are at variance with data obtained during immobilization in plaster casts (32) and that obtained by Graveline and Bälke (51). In discussing their findings, Graybiel and Clark cite the experimental studies of Mueller and Hettinger (111) and those of Rose *et al* (123) on the importance of daily muscular training. Muscular exercise constitutes a training stimulus to a muscle if it exceeds one third the maximum muscular potential. Much less than this value is required to prevent atrophy. If exercise exceeds the one-third threshold value, an increase in muscle strength generally will result. Muscular strength, which is rapidly increased by daily exercise, will show an equally rapid decline on cessation of exercise, while a high muscular potential (50 to 80 percent over the initial strength) could be maintained or even slightly increased by once-a-week maximum contractions. Reductions in muscle strength occur if exercise is limited to once every three weeks. Muscle strength is better maintained by slow versus rapid contraction development.

In Graybiel and Clark's study apparently the small amount of muscular activity involved in getting in and out of the water, moving in bed, etc., was sufficient to meet the required criteria indicated by Mueller and Hettinger. In any event, the muscular movements were far less in Graybiel's experiment than would be experienced under zero g conditions, even if the subjects were confined to a seat or couch. However, under zero g, certain antigravity muscles might not be called into play by crew duties.

For the exposures of a lunar mission, bone demineralization and muscle atrophy are unlikely to be problems unless the crew is severely restrained. If they prove to be problems, exercises of the "Charles Atlas" type should maintain adequate bone density and muscle tone. Individuals who consistently use such exercises show marked increases in bone density due to calcium deposition, as well as the familiar muscular hypertrophy for which the exercises are undertaken.

OTOLITH FUNCTIONS

Long before the advent of space flight, submersion in water was used to study orientation. If visual, kinesthetic, temperature, and buoyancy cues are

largely eliminated by appropriate experimental procedures, orientation to the vertical is thought to be indicative of perception via the labyrinthine senses. Human subjects are easily disoriented with respect to the direction in which they are facing following rotation about their vertical axis. Such disorientation is attributed to the effects of angular acceleration on the semicircular canals. It does not follow, however, that they can be easily disoriented with respect to the direction of the vertical following rotation about an horizontal axis. Rotation about an horizontal axis in a vertically-oriented gravitational field results in a characteristic changing pattern of utricular stimulation. Thus, in addition to the disorienting effects of semicircular canal stimulation, there is another source of stimulation which could, conceivably, enable the retention of orientation with respect to the vertical.

In 1942, Adrian (1) demonstrated a prolonged discharge in the afferent neural connections of the utricles in animals following changes in linear acceleration acting on the body. Presumably, the utricles signal changes in the orientation and/or magnitude of linear acceleration forces only. An individual immersed in liquid, therefore, may be expected to have some basis for orientation in the absence of the usual visual, tactile and other cues. Although the utricles should not be expected to provide him with a continuously available sense of reference for the gravitational vertical, the pattern of change of utricular stimulation may afford a cue as to the orientation of the vertical, or "which way is up", following a few simple changes in position of the head. The study of utricle function thus has significance for zero g space flight.

Immersion, as a method of simulating zero g, in spite of its disadvantages, is believed to have some utility in the study of utricular function. Muller (112) has suggested that the response of immersed subjects might be studied in a liquid-filled cylindrical capsule. The capsule would be rotated about an horizontal axis to eliminate any constant vertical reference for the subject, who is held in a fixed position with respect to the rotation capsule. With a fixed visual display and, in the absence of head movement, a rate of rotation would be sought at which there would be a "fusion" of the stimulating effects of rotation on the utricle. At this rate no vertical reference would be available to the observer. The possibility of utricular cues in the absence of any changes in utricular stimulation is highly questionable. For this reason rotation may not be necessary, if the subject is restrained within the tank and is prevented from making any head movements. The general problem is under study by Levine (96).

Recently, the utricle has been studied under weightlessness as well as submersion. King (86) has investigated postural orientation in decerebrate pigeons by tilting during weightlessness, and Johnson (81) has identified the importance of the utricle for the preception of gravity in lower animals during Keplerian flights. Shock (126) has found impaired orientation to the vertical during submersion and has raised the question of the need for artificial gravity during space flight. Whiteside (164) has

tested orientation as measured by pointing during submersion in water up to the neck. Some loss of directional sense was found in this situation even though the utricular sense was not diminished. The loss was attributed to the altered muscle balance, absence of visual information and reduced proprioceptive cues. The data of Pearson and Hauty (118), obtained by lateral tilt in a dark room, in which the subject returns himself to the preconceived vertical, suggests that some proprioceptive learning may occur.

Many attempts have been made to measure the threshold of the utricles for changes in the resultant linear acceleration. Reported threshold values range from 0.00034 to 0.010 g or higher. A number of determinations have been made on tilt tables in which the subject reported the minimal detectable change in table orientation when the angular accelerations of the table were sufficiently low to avoid stimulation of the semicircular canals. Such experiments have proved of little value because of the number of postural cues available; i.e., tactile stimuli from restraining straps, noise and mechanical irregularities of table motion. More reliable data were obtained by Graybiel and Patterson (59) in terms of the oculogravic illusion. They reported a threshold of 0.000344 g for subjects in the sitting position and 0.00203 g for subjects lying on their sides.

In 1928 Quix (120) reported the presence of a "blind spot" in the utricular sense for subjects in a supine position with the head depressed. Knight (89) attempted to repeat the experiment of Quix under water. Although he found higher thresholds with the head oriented downward, he was unable to obtain clear-cut, quantitative results.

Stigler (135), in 1912, attempted to measure the orientation of swimmers after they had been rotated on a bar while completely submerged. In these experiments the eyes and ears were covered to eliminate visual and auditory cues. Subjects were instructed to point upward upon termination of the rotation. Apparently they were seldom able to do this accurately; the experiment was reported as unpleasant and anxiety-provoking and was terminated because of the subjects' inability to hold their breath long enough for adequate observations.

Recently Brown (15) has repeated these observations in the U.S. Navy Diving Tank at New London. Three specific experimental questions were posed: (1) When submerged in a tank at a point near neutral bouyancy can the subject, placed in some random orientation after several disorientating turns by the experimenter, point correctly in the direction of the vertical without any gross movements of the head? (2) If he is unable to point correctly in the direction of the vertical, can he, after some exploratory head movements, point in the vertical direction? (3) How accurately can he orient his entire body to the vertical and swim in the direction of the surface?

The experimental procedures previously used were refined in the following particulars: (1) little if any temperature gradient was present in the tank and, therefore, thermal cues were minimal; (2) experiments were performed at neutral bouyancy; and (3)

the subjects were experienced divers who could hold their breath sufficiently long for the experimental procedure without exhaling and producing bubbles. Visual cues were eliminated by an opaque face mask. In spite of the probable presence of residual cues, in addition to those provided by the utricles; i.e., difference in density of various parts of the body, slight positive or negative bouyancy, the relation of accuracy of orientation to the terminal position at the end of rotation and the improvement of orientation following head movement were interpreted to indicate that the utricular sense was prominent in this situation. Trials which were terminated in the head-backward, face-upward position or the head-downward position resulted in greater deviation from correct orientation than trials terminating with the head up or forward and were comparable with the results of earlier experiments.

Although the existence of a utricular sense has been questioned (63), few present-day investigators doubt it. Its function has probably never been measured acting all by itself. Gray (53) has pointed out that its normal function is in conjunction with the semicircular canals and it probably should not be considered an independent sensory component. Recent studies by Johnson and Taylor (82) have directly attacked the problem of separating otolithic and semicircular canal function. Using a counter-rotating turntable mounted on a second turntable, revolution without rotation may be produced. Although the subject is being rotated on one turntable, the counter-rotation of the second results in the subject always facing in the same direction. Using glass models of the equilibrium organs, it has been demonstrated that only linear accelerations are produced during such exposures and tilting of after-images are attributable to otolithic function alone.

SEMICIRCULAR CANAL PHENOMENA

When a subject is passively rotated in one plane and turns his head in another, a subjective sensation of rotation in a plane approximately orthogonal to the other two is produced. The total sensation is complex. For instance, the sensations of angular speed and displacement may be discordant, the plane of apparent body rotation may shift, visual illusions may be perceived, and symptoms referable to many body systems produced.

Of particular interest has been the so-called oculogyral illusion which may be defined as the apparent motion of objects in the visual field having its genesis in stimulation of the semicircular canals by Coriolis accelerations. Visual illusions related to stimulation of the otolith organs are called oculogravic illusions. The oculogyral illusion has been used as an experimental measure of semicircular canal stimulation. Another experimental measure is vestibular nystagmus (oscillatory motion of the eyes) produced under similar circumstances. Both measures may be used to follow the time course of the adaptation to vestibular stimulation. The oculogyral illusion is not related perfectly to visual nystagmus (67) but corresponds well under certain experimental conditions.

Recently, Hallpike and Hood (67) have developed quantitative evidence of the relation between nystagmus and the oculogyral illusion and have offered evidence to substantiate Steinhausen's general theory of the cupola mechanism (133) and the physical constants of the system assigned to it by Van Egmond and his co-workers (153).

Steinhausen was able to establish that the cupola is hinged upon the crista and fills the lumen of the ampulla. Following displacement, the cupola returns slowly to the rest position under the influence of its own restoring force. The characterization of the cupola as a torsion pendulum has made possible the calculation of its responses by means of appropriate differential equations. This was carried out by Van Egmond and it is now possible to explain the lengthy after-period of post-rotational sensation in terms of the slow return of the cupola to its rest position.

The physiological responses of the cupola to sustained angular accelerations appear to exhibit no systematic relationships, useful in the physiological sense, with the various physical quanta such as angular velocity, angular acceleration, etc. inherent in the stimulus. Although the maximal cupola deflection increases linearly with acceleration magnitude, in the initial course of application of these accelerations the moment-to-moment values of the cupola deflection exhibit no constant relationship either to the magnitude of the acceleration being applied or to the angular velocity attained. This physiological "irrelevance" of the cupola response to constant acceleration of this kind is usually referred to as the unphysiological nature of the stimulus which lies outside the range of motions normally experienced by the head. By contrast, the response of the cupola, under normal impulsive conditions of head movement, exhibits a much closer relationship to the physical characteristics of the stimulus, in particular its angular velocity. It appears that, unless a period of constant velocity intervenes between accelerative and decelerative phases, the cupola deflection is at all times proportional to the velocity of head movement. In general, the time-velocity curve of a normal impulsive head movement is accurately reproduced by the time-deflection curve of the cupola movement to which it gives rise.

THE SLOW ROTATION ROOM

Recently the problem of the tolerance of human subjects to prolonged residence in a rotating environment has been studied in partial simulation of the environment which might be encountered in a rotating space station. A nearly circular, windowless room has been constructed around the center post of the Pensacola human centrifuge. The room is 15 feet in diameter and seven feet high and may be driven at constant velocity (± 2.5 percent) at rates from 1.7 to 10 rpm.

In such an environment, random or planned head movements stimulate the semicircular canals as the result of the angular velocity of the head motion itself and of changes in the orientation of the several canals to the plane of rotation of the room. If the head is

displaced parallel to the axis of rotation, or laterally in the same plane of rotation, no stimulation occurs. Stimulation results when the head is turned about an axis parallel to the axis of rotation. Turning the head about other axes results in a complex pattern of stimulation as the direction of the forces changes with respect to the several canals. The magnitude of the effects depend on the specific direction and velocity of head motion and the velocity of the room.

While it is theoretically possible to move the head in such an environment without stimulating the semicircular canals, practically, this does not occur. If the head is fixed, the otolith organs are subjected to a constant force which is the resultant of the radial and gravitational forces. However, its direction deviates from the usual gravitational direction, giving rise to the oculogravic illusion. Rotation of the head about an axis parallel to the room axis alters the direction but not the magnitude of the resultant force on the otolith organs.

Studies performed to date in the rotating room (24, 25, 56, 58, 110) support the notion that prolonged constant rotation *per se*, within the range studied (1.7 - 10 rpm) does not interfere with gross task performance. The dominant stimulus is the random bizarre stimulation of the semicircular canals, resulting from head motion. The most prominent change in performance was in motivation towards tasks. Motivation was markedly affected by the occurrence of motion sickness (canal sickness) in the subjects. Sickness resulted in voluntary limitations of head motion and in excessive sleeping. Decrements in walking and body-sway tests were substantial during and immediately following rotation. Two subjects showed decrements and subsequent adaptation on the arithmetic test. No decrements were observed in a number of tests of muscle strength and coordination including eye-hand coordination.

ADAPTATION

Whether man can adapt to the subjective and autonomic manifestations produced by head motion in a rotating environment is a subject of some significance for the case of rotating spacecraft. Observations by Graybiel and his co-workers (57) in the slow-rotation room suggest that such adaptation may occur. By the use of a tilt-chair the time course of adaptation to the oculogyral illusion was followed. Subjects were selected to give a wide range of variations. In subjects least susceptible to canal sickness, adaptation occurred in as little time as 16 hours; the illusion could only be perceived at 10 rpm and then only during active head movements. The most sensitive subject perceived the illusion until the last test period at 5.4 rpm and was not tested at 10 rpm because of severe symptoms.

The results of these experiments indicate considerable capacity in some subjects for habituation to an unusual sensory input. Illusions and disturbing autonomic reactions which initially accompany them are substantially reduced and in some subjects disappear during the course of 64 hours of almost continual rotation. As indicated by the oculogyral illusion, most of the decline occurs within the first

16 hours. Following cessation of rotation, illusions are produced by head rotation in the opposite direction, but symptoms are shorter in duration. Although greater responses are produced by active rather than passive movements, it is not clear whether this is due to the greater velocities of head motion, the influence of cervical reflexes, or because of the voluntary nature of the act.

SELECTION AND TRAINING

If rotation is to be used in space as a means of producing artificial gravity, much more needs to be known concerning man's response to this environment. The current data suggest wide individual differences among subjects, which raises the question of selection and training of the crews. Kraus (92) has reviewed this problem and has suggested tests for selection. On the basis of his data, as well as that of Graybiel (57) and others (17, 64, 65, 68, 103), it would appear that something can be accomplished in this direction.

One selection method, cupulometry, deserves emphasis. Cupulometry consists of placing a subject in a rotating chair, darkening the room, and bringing the subject to a desired velocity of rotation at a "subliminal" rate of acceleration. Once the desired velocity is reached, the subject is rotated for a short time to allow the cupola to return to its normal position. The chair is then brought to a smooth but rapid stop within one or two seconds. This process is repeated for a number of different velocities, for the most part between 5 and 60 degrees per second. After each trial the duration of the ocular nystagmus and the duration of post-rotational sensation are measured. Nystagmus cupulograms and sensation cupulograms are produced by plotting the logarithm of the velocity versus the duration of the nystagmus or sensation. DeWitt (34) has indicated that the slope of the cupulogram is primarily a function of habituation to vestibular stimuli, the slope becoming less steep as the subject becomes more accustomed to the stimulus. Motion sickness tendencies could thus be isolated. Studies in this country (84) have, however, only partially verified the Dutch work.

In addition to measures of performance, nystagmus, or visual illusions, other areas of recent study are relevant. For instance, Benson (11) has studied reflex movements (ankle jerk) in response to labyrinthine stimuli. Taylor, Johnson and Sellers (143) have studied cardiovascular changes associated with vestibular stimulation. Something may be learned from a study of figure skaters (105). Observations on motion sickness indicate a strong psychological element (122). If selection and training do not yield a satisfactory solution to this problem, the use of drugs may ultimately provide a way of extending human tolerance (83).

CONCLUSION

A careful review of the physiological functions of the body reveals very few instances in which function is truly gravity-dependent. The stresses of gravity contribute to backache, flat feet and varicose veins. The vascular system of the body is sufficiently marginal in some of its functions so that prolonged standing results in swelling of the feet in normal

people, and the soldier at rigid attention may faint. There is no *a priori* reason, on the other hand, to believe that gravity is necessary for life. In this connection it is important not to confuse the effects of inactivity, characteristic of experiments involving bed rest, confinement, submersion or immobilization, with possible effects of weightlessness *per se*. Bed rest and submersion are not necessarily realistic analogues of weightlessness, particularly weightlessness as experienced aboard a spacecraft in which crew members perform their normal piloting, monitoring and experimental tasks. Inactivity is to be avoided and vehicle designs must allow sufficient room for reasonable movements. As yet there have appeared no published reports of bed-rest or submersion experiments in which realistic crew duties and activities were a part of the experimental regime.

The physiological systems likely to be affected by weightlessness include the musculoskeletal system, the cardiovascular system and the equilibrium sense. While the general metabolic rate of the crew may be decreased by the absence of the requirement to support the body in a gravitational field, the metabolic depression may be largely overridden by activity and exercise. In multimanned vehicles there will be a requirement to move from place to place. Postural changes will occur with considerable frequency and muscle atrophy and bone demineralization from disuse unlikely. The small amount of muscular exercise required to maintain good muscle tone has been pointed out and the relation of muscular exercise, rather than weight-bearing, to bone demineralization discussed. Although the absence of gravity may result in a redistribution of body fluids and an attenuation of reflex activity, other conditions such as the environmental temperature, the local oxygen demands of various tissues as the result of inactivity or exercise, also effect the distribution and the reflex background. Inasmuch as the regulation of the cardiovascular system is extremely complex, further study is warranted; but the findings that completely-submerged skindivers show little change in acceleration tolerance, following 18 hours of submersion, suggest that activity may again largely prevent marked changes.

From the foregoing, it may be concluded that, although direct experimental data is lacking, there is sufficient information upon which to base an intelligent decision as to whether man can tolerate the weightless state or whether the generation of a gravitational field will be required for his well-being. It appears that the physiological effects of either weightlessness or inactivity can be prevented successfully by adequate and appropriate physiological measures and that man can perform his role in space missions of moderate length without decrement due to physiological causes. Interpretation and decisions based upon Titov's experience of nausea must be reserved. Detailed information is not available concerning vehicle motions (tumbling) and his relative sensitivity to head motions under these conditions.

It is valuable in this connection to consider a lunar mission as a whole and the impact of an artificial g environment on its conduct. Following the

launch accelerations, the crew must pass through a weightless phase. Studies of von Beckh (155) have indicated that such transients from acceleration fields to the weightless state may be associated with disorientation although Shepard and Grissom report no significant effect. Sometime after entering the weightless state the craft is set into rotation. During this early phase of the mission to the moon, critical guidance corrections must be made or the decision to abort taken. Because of the effect of rotation on the precision of the guidance and control system and the requirement to make corrections at a maximum distance from the moon, at least two to three hours of weightlessness will be required. Probably at least once during the lunar voyage, rotation must be stopped to carry out path correction. Some course-correction schedules would call for as many as four to five derotations. Rotation must again be stopped in order to insert the craft into lunar orbit. Visual observation of the lunar surface by the crew may require a stable, non-rotating platform as may the use of other lunar observation instruments. The illuminated surface of the moon will be visible for only one hour or less during the three to five-hour orbital period. Exit from lunar orbit, mid-course corrections and terminal guidance before earth re-entry all will require cessation of rotation.

It is thus apparent that, depending upon the precision of the guidance and control system and the requirements of the mission, as few as four or as many as a dozen transients between weightlessness and exposure to gravity may be required. In the worst case of 12 transients (poorest guidance and control), periods of exposure to either weightlessness or artificial gravity would rarely exceed one day for a rotating spacecraft, a time equivalent to the adaptation period of rotation-insensitive individuals. On the other hand, the mission under the best circumstances will always require some exposure to the weightless state.

The structural sophistication required to successfully execute a rotating vehicle is considerable. Important design considerations include the angular velocity of the vehicle, the g-level at the rim, the radius, the rim velocity, the g-gradient on the crew, the velocity of head movement and the ratio of the Coriolis forces to the centrifugal forces (26, 37, 61, 91, 104, 117). Rotation rates and radii necessary to achieve one g appear unrealistic for a lunar mission. If less than one g is achieved, problems of both weightlessness and rotation are likely to appear. It may be argued that the effects of subgravity differ from those of pure weightlessness only in the time course with which they develop. Thus, for subgravity, similar precautions, such as special exercises, may be required.

The presence of gravity in a space vehicle would result in the ready resolution of a number of the mechanical problems of weightlessness. Eating (158), the handling of body waste, the act of micturition (159), the presence of convection, the settling of dust and dirt, and decreased development time for components whose zero-g function has not yet been established, are among the advantages. Crew spaces,

displays and controls, and the mechanisms by which the crew moves about and does work may be more conventional in a partial gravity field (39, 40, 130).

In many of the experimental studies of the equilibrium senses cited in this review, effort was made to isolate the labyrinthine senses by elimination of other cues to orientation. In other studies all orientation senses including the labyrinth, vision and proprioception were present simultaneously. In a spacecraft the crew will always have visual senses for orientation to their equipment and surroundings so that it is important that other sense modalities do not generate conflicting cues leading to illusions. In weightless space, first- and second-order interactions with the gravitational force will be eliminated. The significance of such interactions cannot be deduced from terrestrial experiments, but their absence may result in an enhanced possibility of disorientation. In any case, because weightlessness remains a part of every space mission, problems of selection and training of the crew are likely to be unaltered.

An over-all view of the lunar mission indicates that the weightlessness problem must be subject to experimental test. Two courses of action appear open; first, to proceed, using weightlessness as a design requirement, in gradually increasing steps until sufficient data is generated in orbital flight to reach a firm decision; or, secondly, to probe the problem with biosatellites. It is apparent from the analysis that there is a critical requirement for metabolic and biochemical data on animals and/or man in orbit. Because of the biochemical nature of the required measurements, animal satellite experiments may, of necessity, be limited to "before and after" measurements. Automatic blood and urine collection devices, which operate over a prolonged period under weightlessness, are not known. Serious consideration should be given, however, to the study of experimental animals in manned vehicles in order that detailed measurements might be made without interfering with crew effectiveness.

Metabolic data on the crew may be acquired by measurements of oxygen consumption from the vehicle stores. Such data would reflect only the average activity of the crew and would not provide detail on metabolic rates during sleep or that characteristic of task performance. In addition, oxygen consumption rate must be corrected for cabin gas leakage. Leakage rates could be calculated from measurements of diluent losses.

Dietary intake aboard the vehicle could be well-controlled. Individual measurements of oxygen consumption could be conducted using a lightweight, wedge-type spirometer. Individual dietary intakes and oxygen consumptions for various ranges of activities, combined with average data for the entire crew, should give a good picture of the metabolic requirements of weightless space flight.

Although general metabolic data may be helpful in evaluating the status of man's muscular system, more detailed information should be acquired. A number of methods are available, including the measurement of

muscle girth by one crew member on another, evaluation of muscle strength by a spring-loaded ergometer, electromyographic and chronaxie measurements, and urinary nitrogen and sulfur excretion. Bone demineralization may be followed by "before and after" x-rays and by urinary calcium excretion. Daily urine-volume measurements will be required to follow nitrogen, calcium and electrolyte losses if they should occur.

Many of the significant experiments involve the collection and analysis of fluid samples. It is proposed that blood and urine samples be collected in labeled, capillary tubes. Such tubes could be conveniently stored in the frozen state for subsequent analysis. Consideration also should be given to analysis in orbit. Problems arise, however, with respect to crew training and methodology. It would seem to be possible to teach crew members to collect blood samples from the ear lobe or finger, to measure the daily urine volume and to collect urine samples. Whether the chemical analysis is conducted in orbit or after re-entry, an intensive study and proof of suitable micromethods is in order.

It is apparent that astronauts will require exercise during periods of prolonged weightlessness. The clinical armamentarium in this area is considerable and no problem is envisioned. There appears to be no requirement for power-consuming-massaging or stimulating devices. Although little is known concerning the minimum of threshold exercise necessary to maintain normal muscle or bone integrity, no harm may come from reasonable exercise regimes over the periods of weightlessness envisioned for the near future.

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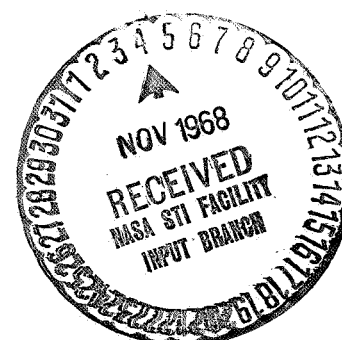
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